A comparative study of mass balance modelling approaches for soil erosion quantification using cesium-137

A.Jha[1), 2)], G.Kirchner[2)]

[1)] University Bremen, Dept. of Physics, 28334 Bremen, Germany
[2)] Federal Office for Radiation Protection, 38226 Salzgitter,
gkirchner@bfs.de

Summary

Soil erosion by water, wind and tillage affects both agriculture and the natural environment. Interest in fallout radionuclides such as ^{90}Sr and ^{137}Cs to study medium term soil erosion (40 yrs) increased in the early 1990's. The mass balance approach used to estimate long-term erosion and sedimentation rates is presented. A modification to improve the model for areas which are subject to deposition of eroded soil is presented. As an example, data from a site close to Berlin are presented. Using our improved mass balance model, ^{137}Cs derived estimations of erosion and deposition rates are presented.

1. Introduction

Studying long-term erosion and sedimentation processes by using man-made and natural radioisotopes is an innovative approach in soil science, which has developed over the past 30 years. Fallout ^{137}Cs is the radionuclide most extensively been used to provide independent measurements of soil-erosion and sediment-deposition rates and patterns [1, 2, 3, 4].

1.1 Erosion measurements using ^{137}Cs

Caesium-137 from atmospheric nuclear-weapons tests in the 1950s and 1960s (Fig.1) is a unique tracer of erosion and sedimentation, since there are no natural sources of ^{137}Cs. Events such as the Chernobyl accident in April 1986 caused regional dispersal of ^{137}Cs that may affect the deposition budget at a specific site.

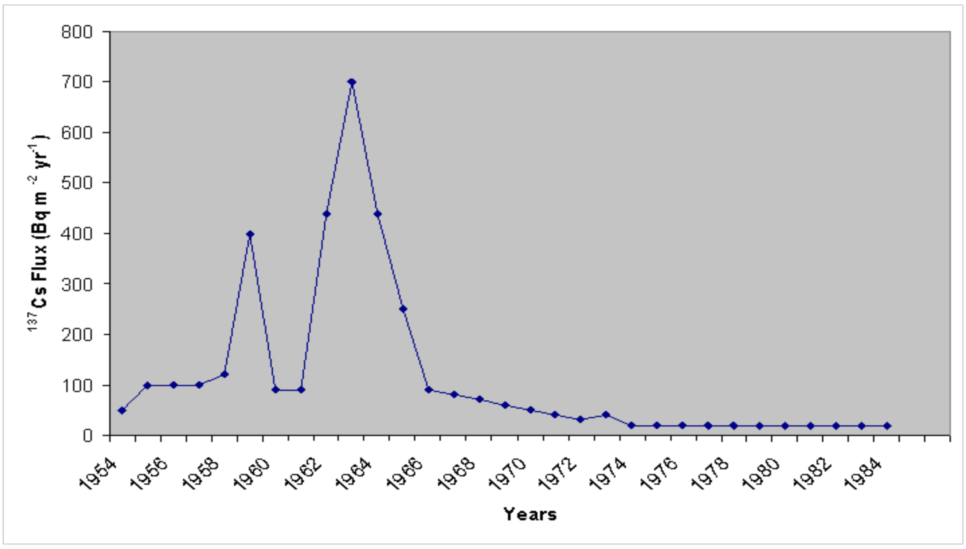

Figure 1: Mean annual ^{137}Cs fallout deposition rates in Germany (50^0 N-60^0 N) (modified from [8])

^{137}Cs can be easily measured by gamma spectroscopy. Using ^{137}Cs is a fast and cheap method to study erosion-deposition processes compared to traditional methods like silt bags.

Because of its long half life, ^{137}Cs may migrate into the soil. Its distribution in soils is affected by spatial variations in deposition rates and by land use. An undisturbed soil will exhibit higher radionuclide activities near the soil surface, which reflects their surficial input and slow downward transport. Plowing homogenizes ^{137}Cs within the plowed layer (Figure 2). The concentration of fallout ^{137}Cs in surface horizons and its slow transport into the soil have allowed using this radioisotope to estimate rates of soil erosion [4, 5, 6].

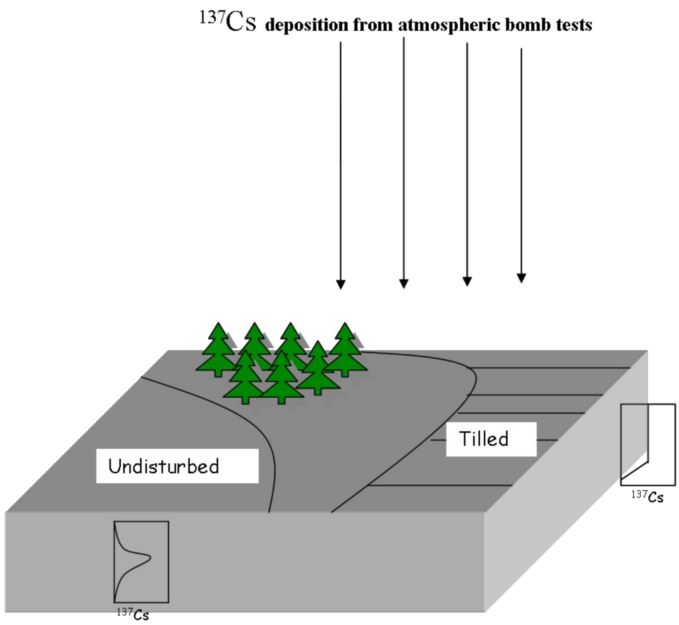

Figure 2: Generalized sketch illustrating the distributions of ^{137}Cs in soils under tillage and undisturbed conditions.

2. Erosion study at Young Moraine regions of Germany

Soil redistribution rates were estimated at a real site in the Young Moraine region of North-East Germany. The sampling was performed on 16th April 2008 at Basedow, a cultivated area north of Berlin (53° 34' N & 13° 80' E). Figure 3a shows the transect used for sampling. Sites which were not affected by soil loss or deposition and thus reflect atmospheric inputs of ^{137}Cs and its decay were taken as reference sites [7]. The sectioned soil cores were collected from depths of 0-10 cm in increments of 2 cm and from depths below 10 cm in increments of 5 cm. Samples from 15 measurement sites and 2 reference sites were taken. The soil was dried at 105°C, sieved, filled in aluminium bottles and analysed by gamma spectroscopy. Figure 3 shows the measured ^{137}Cs inventories along the transect under study.

2.1 Conventional mass balance erosion/deposition model

The standard approach to erosion assessment using ^{137}Cs is described and discussed in detail elsewhere [1, 2, 3, 4]. The inventory of ^{137}Cs at the measurement points (A_t) is compared with a reference inventory (A_{ref}) taken at areas not subject to soil erosion or deposition. If $A_t < A_{ref,}$ erosion is assumed to have occurred; $A_t > A_{ref}$ is assumed to result from soil deposition. The ^{137}Cs concentration may vary due to cultivation practices such as ploughing. The rate of soil erosion and deposition can be estimated as:

$$Y_{ero} = \frac{10 \times d \times \rho_b}{P \times \Delta t} \left[1 - (1 - X)^{\frac{1}{t_n - 1963}} \right] \qquad (1)$$

Where Y_{ero} is the erosion rate (t ha^{-1} yr^{-1}), X the reduction in total ^{137}Cs inventory ($\frac{A_{ref} - A_t}{A_{ref}}$), d the ploughing depth (m), t_n is the time step ($t_n = t_0 + n \cdot \Delta t, n = 0 \text{ set to } t_0 = 1963$) and ρ_b the soil's bulk density (kg m^{-3}).

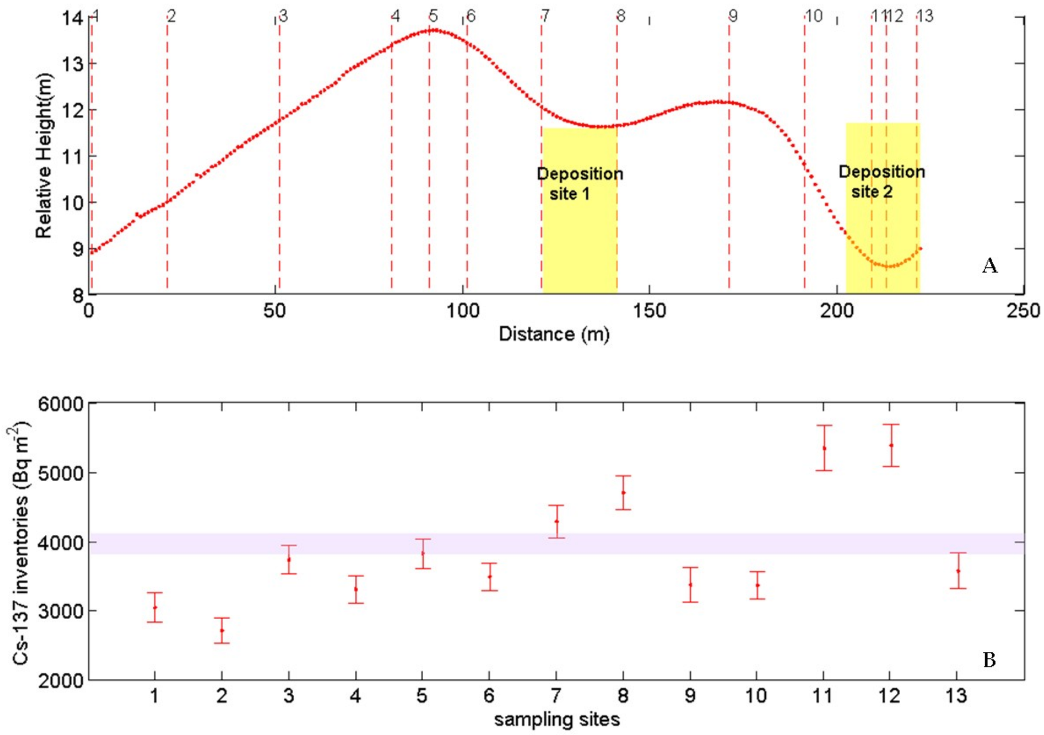

Figure 3: Top: study transect at Basedow; bottom: Activity distribution of ^{137}Cs along the transect; the dotted band gives the 95% uncertainty interval of the reference activity, error bars denote sample standard deviations.

The eroded soil is carried by the force of water and wind and is deposited. The mean of the concentration (Bq m^{-3}) of ^{137}Cs deposited annually from the upslope areas, $C_d(t_l)$, is given by eqn. (2), the deposition rate at year n is calculated by eqn. (3):

$$C_d(t_l) = \frac{\sum_{i=1}^{K} C_{e_i}(t_l) \cdot \Delta Z_i \cdot S_i \cdot P_i}{\sum_{i=1}^{K} \Delta Z_i \cdot S_i \cdot P_i} \quad ,l=1...N \qquad (2)$$

$$Y_{dep} = 10 \times \rho_b \times \left(\frac{A(t_n) - A_{ref}}{\sum_{l=1}^{N} C_d(t_l)} \right) \qquad (3)$$

Here $C_{e_i}(t_l)$ denotes the ^{137}Cs concentration mobilized from eroded area S_i (Bq m^{-3}), ΔZ_i the height of soil eroded during a time step t_n, S_i the slope area represented by point i (m^2), P is the particle size correction factor, K is the number of eroding areas and N is the year of sampling.

2.2 Improved Mass Balance Deposition Model

The basic assumption of the mass balance approach is that the mass of soil eroded must be deposited in the area studied. The deposition sites thus reflect the amount of dislocated soil. The initial concentration of soil containing ^{137}Cs is C_0. In the following years a constant layer, ΔZ_d, of soil eroded from upslope areas is deposited in the area down the slope. As a consequence the depth, to which the soil (and the ^{137}Cs sorbed to it) is homogenized due to ploughing, changes annually. This effect that is neglected in eqn. (3) is taken into account in the following.

The deposited concentration $\bar{C}(t_1)$ (Bq m^{-3}) is then estimated as

$$\bar{C}(t_0+n\times\Delta t)=\frac{(d-\Delta z)\times C_1(t_0+(n-1)\times\Delta t)+C_d(n\times\Delta t)\times\Delta z}{d}\times P\times e^{-\lambda\times\Delta t} \qquad (4)$$

where C_d (Bq m^{-3}) is the ^{137}Cs concentration of the eroded soil given by eqn. (2).

The deposition rate (t ha^{-1} yr^{-1}) is estimated as

$$\bar{Y}=10\times\rho_b\times\left(\frac{A(t_n)-A_{ref}}{\sum_{1=1}^{N}\bar{C}(t_1)}\right) \qquad (5)$$

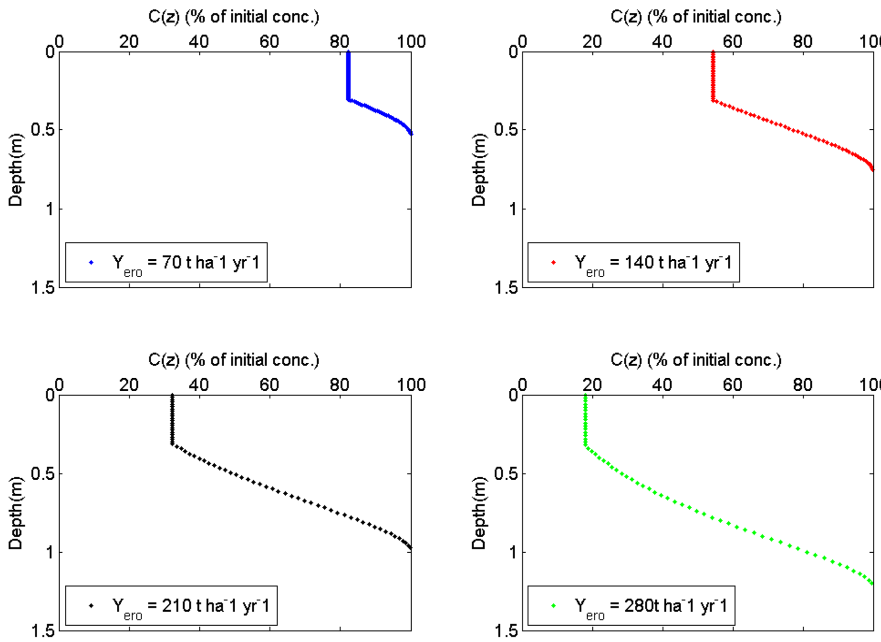

Figure 4: ^{137}Cs concentration at the depositional site predicted for 2008 by eqn. (4) assuming different erosion rates.

As a first step to explore the effect of the improvement supposed in our soil deposition model given by Eqn. (4), numerical simulations were performed. Figure 4 shows depth distributions of deposited ^{137}Cs at the

depositional site for four erosion rates as predicted for the year 2008 using the deposition model of Eqn. (4). In Fig.4 the maximum of the ^{137}Cs concentration corresponds to the ^{137}Cs fallout in 1963, and thereafter its concentration decreases each year, since at the eroding site each ploughing leads to mixing with some soil without ^{137}Cs. The homogeneous distribution of ^{137}Cs in the upper 30 cm results from ploughing.

3. Estimation of deposition rates using the improved mass balance model

The ^{137}Cs mass balance model of Eqn. (1) was used for calculating erosion rates at the two segments of our experimental site shown in Fig. 3. The deposition rates calculated by equations (3) and (5) are given in Table 1. The differences between deposition and erosion rates (Δ_{DE}) show that the deposition rates calculated by eqn. (3) at both sites violate the mass balance of eroded and deposited soil.

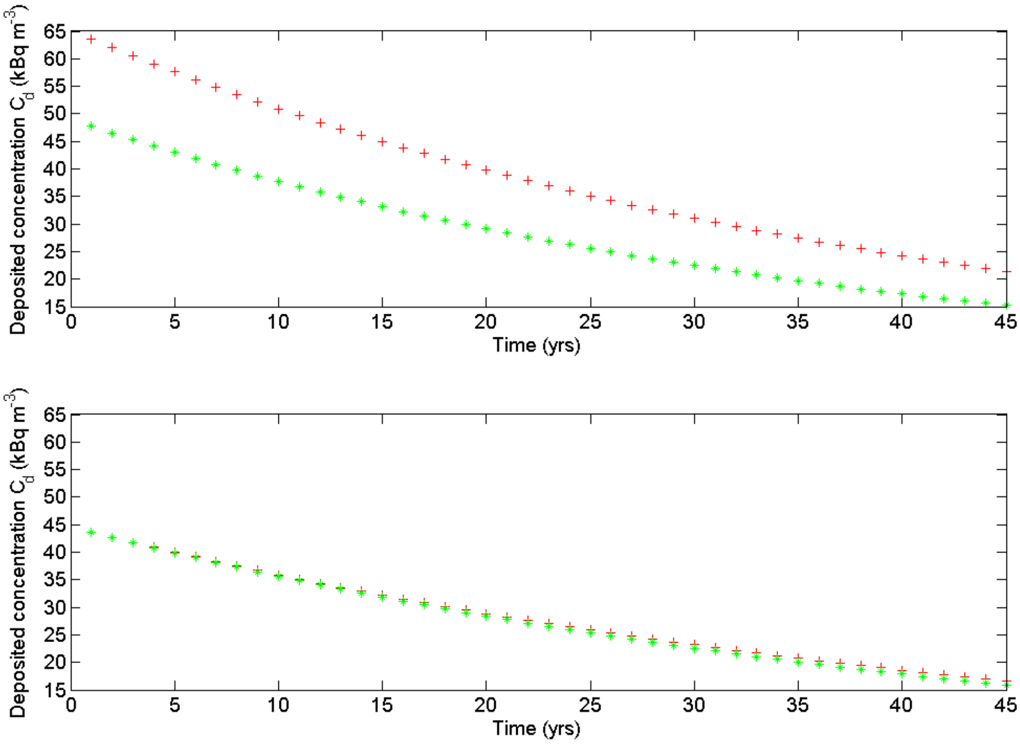

Figure 5: Simulations of deposited ^{137}Cs concentrations at the two segments (top: site 1, bottom: site 2 of Fig. 3) based on eqn. (3) (* signs) and (5) (+ signs), respectively.

Fig. 5 show that eqn. (3) overestimates deposited concentrations and, as a consequence, underestimates deposition rates compared to the improved model of eqn. (5). This result from including the effect of annual reduction of ^{137}Cs by the fraction no longer ploughed due to the increase in soil deposited.

Table1: Soil budget for Basedow site derived from two mass balance deposition models; Δ_{DE} gives the difference between deposition and erosion rates

	Erosion rates (t ha^{-1} yr^{-1})	**Deposition rates calculated (t ha^{-1} yr^{-1})**			
		Eqn.(3)	**Δ_{DE}**	**Eqn.(5)**	**Δ_{DE}**
Site 1	-18	7	11	17	1
Site 2	-44	26	18	46	2

4. Acknowledgements

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